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3.	Full name, address and postcode of the or of each applicant *(underline all surnames)*	The University Court of the University of Glasgow and The University of Strathclyde (See Additional Sheet) (over)
	Patents ADP number *(if you know it)*	
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4.	Title of the invention	Improvements in and Relating to Optical Devices
5.	Name of your agent *(if you have one)* "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	CRUIKSHANK & FAIRWEATHER 19 ROYAL EXCHANGE SQUARE GLASGOW G1 3AE UNITED KINGDOM
	Patents ADP number *(if you know it)*	547002

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12. Name and daytime telephone number of person to contact in the United Kingdom Dr David Moreland 0141 221 5767

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The University Court of the University of Glasgow
2 The Square
University Avenue
Glasgow
G12 8DQ

433942001

The University of Strathclyde
McCance Building
16 Richmond Street
Glasgow
G1 1XQ

798496003

IMPROVEMENTS IN AND RELATING TO OPTICAL DEVICES

TECHNICAL FIELD OF INVENTION

The present invention relates to an improved optical device, method and apparatus e.g. for use in improved optical communications or processing. In particular the invention relates to a device, method and apparatus which utilises at least the orbital angular momentum of photons to allow a plurality of states of information to be transmitted optically.

BACKGROUND TO INVENTION

It is known that photons can carry both spin and orbital angular momentum. The spin which a photon carries is associated with the polarisation of the photon, and the orbital angular momentum is associated with the azimuthal phase of the complex electric field. The polarisation of a single photon is described by a state in two-dimensional space, the Eigenvalues of which are $\pm\hbar$, or more simply can be considered as right hand spin and left hand spin. Photon polarisation provides a useful physical realisation of a single qubit and is widely employed in demonstrations of quantum key distribution. However the measurements of the polarisation, that is

identification of right hand spin or left hand spin, only provide for the transmittal of one bit/piece of information by a photon, that one bit/piece of information only providing a bi-state result, for example, left and right which could be interpreted as yes and no respectively. Therefore, in terms of optical communication, the information which can be carried by a single photon is limited when read out is reliant on the spin of the photon.

It has been noted, however, that the infinite number of orthogonal states of orbital angular momentum places no limits on the number of bits of information that can be carried by a single photon. Furthermore, the ability to create states with different orbital angular momenta and superpositions of these states allows the realisation of quNits, that is the quantum states in an N-dimensional space with single photons. However, at the moment it is only possible to identify the value of orbital angular momentum when a plurality of photons possessing the orbital angular momentum are made to interfere. Using an arrangement such as that shown in Figure 1 which is a Mach-Zehnder interferometer with a Dove prism inserted into one arm, input light interferes with its own mirror image. In the case of light with l intertwined helical

phase fronts the interference pattern has $2l$ radial fringes. In the arrangement shown, $l = 2$ and therefore 4 fringes can be seen. This arrangement allows an arbitrary number of states to be distinguished between but in order to form the required fringe pattern, many photons are needed.

In Figure 2 there is shown a prior art arrangement which can identify orbital angular momentum at a single photon level. In this arrangement the photons having orbital angular momentum, which in this case is $l = 2$, are projected through a $\Delta l = -2$ hologram. This hologram allows phase fronts of the light modes, if $l = 2$ to be flattened. This means the beam, now with planar phase fronts can be focussed through a pin hole behind which is positioned a detector. As only $l = 2$ light modes will be flattened by the $\Delta l = -2$ hologram, no light will be transmitted through the pinhole, and therefore no light detected, if l takes any other value, i.e. $l \neq 2$. Whilst this arrangement works at a single photon level, it can only test for one particular state of orbital angular momentum. Therefore, this arrangement is such that it is only possible to achieve a bi-state result, that is only the question "Does $l = x$?" (where x equals one of -n,

....., -3, -2, -1, 0, 1, 2, 3,..,n) can be considered the answer to which can only be yes or no.

An object of at least one aspect of the present invention is to obviate or at least mitigate at least one of the aforementioned problems.

A further object of at least one aspect of the present invention is to provide a means for determining, at a single photon level, a value of orbital angular momentum possessed by the photon, providing a multi-channel device for determining the orbital angular momentum of a single photon.

SUMMARY OF INVENTION

According to a first aspect of the present invention there is provided an optical device comprising:

at least one input;

a plurality of outputs;

means for directing at least one photon from the input to a selected of the outputs, the selection being dependent upon at least an orbital angular momentum of the/each at least one photon.

The orbital angular momentum is taken to mean the property of a light beam such that upon rotation about a beam axis a phase shift is introduced.

The selection may be dependent upon:

orbital angular momentum (OAM) solely;

orbital angular momentum and spin angular momentum (SAM) individually; or

orbital angular momentum and spin angular momentum combined (i.e. total angular momentum).

Preferably the means for directing comprises at least one interferometer.

Preferably the or each interferometer may include means for inducing, in use, a rotation of a light mode of a photon in at least one arm of the interferometer.

Preferably the means for inducing a rotation further comprises at least a first prism and a second prism. Conveniently at least one prism may be positioned in each arm of the interferometer.

Alternatively the first prism and second prism may be positioned in one arm of the interferometer.

Conveniently the at least first prism positioned in a first arm of the interferometer is rotated with respect to the at least second prism positioned in a second arm of the interferometer.

In this arrangement, the term rotated is used to denote that the second prism is turned through an angle of α around the second optical path, with respect to the

orientation of the first prism in the first optical path.

Preferably the at least first prism and second prism introduce a phase shift in each passing photon.

Conveniently each prism is a Dove prism.

Dove prisms are know and act to cause a inversion of a transverse cross-section of an optical beam transmitting through the prism.

Conveniently the optical device comprises a one piece device and is preferably a monolithic block.

The device may include means for rotation of a polarisation state (and hence spin angular momentum) of a photon or photons.

The means for rotation may allow an output of the device to be determined by total angular momentum of a photon or photons, not solely OAM.

The means for rotation may be at least one half-wave retarder. Alternatively the means for rotation may be at least one quarter wave retarder.

Conveniently the means for rotation may be disposed within the or each interferometer.

Alternatively the means for rotation may be disposed outwith the or each interferometer.

According to a second aspect of the present invention there is provided an optical device comprising:

an input;

a first beam splitting means;

a second beam splitting means;

a first reflective means;

a second reflective means;

a first prism;

a second prism; and

at least a first output and a second output,

wherein the first beam splitting means, the second beam splitting means, the first reflective means, and the second reflective means are arranged to form an interferometer arrangement, with the first prism disposed in a first arm of the interferometer arrangement and the second prism disposed in a second arm of the interferometer arrangement, the input leading to the first beam splitting means and the at least first output and second output leading from the second beam splitting means, and wherein, in use,

at least one photon is input into the device which determines, based on an orbital angular momentum of the photon, the output to which the photon will pass.

Preferably the first prism is rotated with respect to the second prism.

Preferably the first prism and second prism

introduce a phase shift in the or each passing photon.

Conveniently each prism is a Dove prism.

Conveniently the optical device comprises a one piece device, this is preferably a monolithic block.

According to a third aspect of the present invention there is provided an optical apparatus comprising a plurality cascaded optical devices according to the first aspect or second aspect of the invention wherein the devices are arranged with an at least one output of one optical device optically communicating with another optical device.

The apparatus may comprise an optical signal processing apparatus.

Preferably a hologram may be disposed between an output of the one optical device and an input of the other optical device.

Conveniently, in use, the hologram acts to increase the orbital angular momentum of the or each photon which passes through the hologram.

According to a fourth aspect of the present invention there is provided an optical system including at least one optical device or optical apparatus according to the first, second or third aspects of the present invention.

Preferably, the optical device or apparatus provides the system with at least two possible output groups of output photons or states, the groups or states being selected by the optical device or apparatus depending on an orbital angular momentum feature of the input photon.

Preferably the system further comprises a detector arrangement to detect a state of at least one output of the optical device or apparatus.

Preferably the optical system is an optical communications system, and preferably a free space optical communication system.

It will be appreciated that although the device/apparatus/system of the present invention may be adapted for use at any suitable wavelength within the electromagnetic spectrum, the device/apparatus/system may be adapted for use in the near infrared spectrum or visible spectrum, particularly 700nm to 3μm, and most preferably 1.3μm to 1.6μm.

According to a fifth aspect of the present invention there is provided a method of determining a feature of orbital angular momentum of a or each photon in an optical signal, the method comprising the steps of:

providing an optical device comprising:

at least one input;

a plurality of outputs;

means for directing at least one photon from the input to a selected of the outputs, the selection being dependent upon an orbital angular momentum of the/each at least one photon;

inputting the or each photon into the optical device;

detecting a feature of the orbital angular momentum of the or each photon;

directing the or each photon to a selected one of a plurality of outputs, the selected output for the or each photon being selected by the detected property of the or photon being selected by the detected property of the or each photon.

According to a sixth aspect of the present invention there is provided a method of optical communication, the method comprising the steps of:

providing an optical detection system comprising at least one optical device and a detection means;

receiving said at least one photon;

passing at least one received photon through the optical device comprising at least one optical device so as to determine an orbital angular momentum of said at least one photon;

directing the at least one photon from the optical

device to the detection means so as to identify said feature of orbital angular momentum of said photon.

Preferably the method further comprises the steps of:

providing at least one optical transmission system; and

transmitting at least one photon to be received by said optical detection system.

According to a seventh aspect of the present invention there is provided a prism, the prism comprising:-

an input;

an output;

means for inverting a transverse cross-section of an optical beam or light mode transmitted through the prism without changing the polarisation state.

Preferably the input and the output are normal to an optical beam transmission axis.

Preferably the prism is formed of optical quality glass, in particular it may be formed of BK7.

According to an eighth aspect of the present invention there is provided a prism, the prism comprising:

a first end face;

a second end face, arranged substantially parallel to said first end face;

and a side face, disposed between said first end face and said second end face, the side face being formed of two planar areas disposed in a inwardly orientated "V" shape.

In this arrangement, inwardly orientated is used to identify the orientation of the face with respect to the body of the prism.

Conveniently the prism acts to invert a transverse cross-section of an optical beam transmitted through the prism.

Conveniently the prism is polarisation insensitive when an optical beam is input to the prism via an end face.

According to a ninth aspect of the present invention there is provided an optical device comprising two prisms according to a seventh aspect of the present invention.

Preferably the device further comprises two beam splitters.

Conveniently the device is a block unit, with planar faces of each component allowing each component to be arranged directly adjacent each other component.

Conveniently the block unit is a monolithic block.

Preferably a plurality of said devices are cascaded to form an optical apparatus.

Preferably an optical communication system may be formed using said optical device or optical apparatus.

BRIEF DESCRIPTION OF DRAWINGS

These and other aspects of the present invention will be described, by way of example only, with reference to the following description when taken in combination with the accompanying drawings which show:-

Figure 1 - a schematic representation of a first prior art system for measuring the orbital angular momentum of light;

Figure 2 - a schematic prior art system for identifying a particular value of orbital angular momentum of photons;

Figure 3(a) - a schematic of an unrotated phase structure;

Figure 3(b) - a schematic representation of the phase structure of Figure 3(a) having been rotated

Figure 4 - grayscale representations of phase profiles of non-rotated and rotated light beams;

Figure 5 - a schematic representation of a device for detecting orbital angular momentum according to a

first embodiment of the present invention;

Figure 6 - a schematic representation of sorting stages of an optical apparatus according to a second embodiment of the present invention;

Figure 7 - photographic images of experimental results obtained using the optical device of the first embodiment of the present invention;

Figure 8 - photographic images of experimental results obtained at single photon level using the optical apparatus of the second embodiment the present invention;

Figure 9 - a schematic representation of an optical communication system including an optical device or apparatus of the present invention;

Figure 10 - a schematic representation of a device according to a third embodiment of the present invention;

Figure 11 -photographic images obtained using the device of Figure 10;

Figure 12 - a schematic representation of a prism suitable for use in a device of the present invention; and

Figure 13 - a schematic representation of a device according to a fourth embodiment of the present invention.

Figure 14 - a schematic representation of a device

according to a fifth embodiment of the present invention;

DETAILED DESCRIPTION OF DRAWINGS

An azimuthal phase ramp of a transverse cross-section of wave fronts result in surfaces of constant phase that are shaped like helices. With references to Figure 3(a), there is shown a schematic representation of the phase structure, from 0 to 2π of a lightmode which has an orbital angular momentum of $l = 1$ and an $\exp(il\phi)$ phase structure. As can be seen the phase structure 10 has a spiral-type form which in this case comprises, as $l = 1$, a single helix. Below this, is illustrated a grey scale projection 12 of the phase front which is indicative of the single helix structure, with only one leading edge visible.

In Figure 3(b), there is illustrated the spiral phase structure of Figure 3(a) upon having been rotated through π. As can be seen, the π rotation results in the projection of the phase front of the structure, now $\exp(il(\pi+\phi))$, being out of phase by $l\pi$ with the non-rotated projection. The phase structure when $l=1$ therefore requires a 360° rotation before repeat symmetry would be achieved.

In Figure 4, there is illustrated a comparison of

transverse phase cross-sections for rotated, and non rotated beams having l=0,1,2,3 and 4. The upper row of cross sections illustrate the exp($il\phi$) phase front structure for each of the orbital angular momentum values. The lower row of cross sections show the corresponding exp($il(\pi+\phi)$)phase front structure for the orbital angular momentum values = 0, 1, 2, 3 and 4 upon rotation of the phase front through π. The bottom line of the chart which illustrates ΔΨ shows that for even values of l, rotational symmetry is achieved at 180°. However, for odd values of l, the rotated beam is out of phase, by π, with the non-rotated beam after a rotation through π.

In Figure 5 there is shown a first embodiment of an optical device which, in this case, comprises a Mach-Zehnder interferometer and two Dove prisms. In particular the device 18 comprises a first beam splitter 20, a second beam splitter 22, a first mirror 24, a second mirror 26, a first Dove prism 28 and a second Dove prism 30.

A beam which is input into the device 18 enters the first beam splitter 20 where it is split one part of the beam being transmitted along optical path 32 through the first Dove prism 28 after which it is reflected from the

first mirror 24 before passing through the second beam splitter 22. The second part of the beam is transmitted along optical path 34, and reflects off the second mirror 26 before passing through the second Dove prism 30 after which it transmits through beam splitter 22.

A Dove prism, such as prisms 28 and 30 in the device 18 inverts the transverse cross section of any beam transmitted through the prism. Therefore the inclusion of a Dove prism 28, 30 on each optical path 32, 34 with the second Dove prism 30 being rotated through an angle of $\alpha / 2$ with respect to the first Dove prism 28 has the effect of rotating a passing optical beam through an angle of α. In the arrangement illustrated, $\alpha/2 = \pi/2$ and hence the relative phase difference between the two optical paths 32, 34 of the interferometer is $\Delta\Psi = l\pi$. By adjusting the path length of the interferometer arrangement accordingly, photons with even l are output from beam splitter 22 along optical path A1, and photons with odd l are output from beam splitter 22 along optical path B1. If the input state of photons input into the device 18 is a mixture of even and odd l components, then these components are "sorted" into an even channel and an odd channel when output.

In this device 18, the orbital angular momentum

measurement 'sorts' $\exp(il\phi)$ according to the value of l, relying on the $\exp(il\phi)$ phase structure of the transverse mode of the photon. As shown in Figures 3(a), 3(b) and 4, on rotation of the beam through an angle α, this dependence becomes $\exp(il(\phi+\alpha))$. This corresponds to a phase shift of $\Delta\Psi = l\alpha$ which is a manifestation of a geometrical phase. For particular combinations of l and α the rotated beam may either be in or out of phase with respect to the original phase of the beam. For example, when $\alpha = \pi$ a beam with even l is in phase with the original phase but a beam with odd l rotated by the same angle is out of phase by π. By incorporating this rotation into the arms of a two-beam interferometer which forms the basis of device 18, the phase shift between the two arms becomes l-dependent. This means that for different angles of rotation, constructive and destructive interferences occurs for different values or classes of l which is exploited as detailed by the insertion of dove prisms into the arms of the interferometer.

In order to extend this device further to provide a multi channel output, an optical apparatus can be formed of a plurality of devices 18. In such an apparatus, each device arranged as described with reference to Figure 5

a first device has a beam input into it and further devices are cascaded from the initial device. In each of these cascaded devices, different rotation angles would be implemented and schematic illustrations of such a cascaded arrangement is shown in Figure 6.

In the illustration of Figure 6, there is shown the first three stages of the "sorting" scheme of an optical apparatus 35 comprising three layers of cascaded devices. Each device 18 has two outputs, Ax and Bx respectively. The device 18a of the first 'sorting' stage comprises dove prisms rotated to introduce a phase shift of $\alpha = \pi$ and therefore the outputs along optical paths A1 and B1 respectively are sorted in multiples of two, that is even values of l are output along optical path A1 and odd values of l are output along optical path B1.

If we then follow the transmission of odd l photons these are passed through a $\Delta l = 1$ hologram 36, which is generated using standard photographic techniques so that they become even l photons. The inclusion of the $\Delta l=1$ hologram is necessary as each device 'sorts' even and odd multiples of powers of 2, this means that in order for the photons output along B1 which currently have $l=\ldots-1,$ 1, 3, 5, undergo a further 'sorting' stage a value of 1 must be added, or alternatively subtracted, to each odd

value, resulting in $l = \ldots 0, 2, 4, 6$ etc. The device 18b through which these photons then pass on the second stage, introduces a phase shift of $\alpha = \pi/2$ due to phase shift means that this device 18b can thus sort the input even l photons into even and odd multiples of two, with even multiples of two, being output along optical path C2 and odd multiples of 2, that is l=2, 6, 10..... being output along D2.

At the third cascade stage, $\Delta l = 2$ holograms 38a and 38b are placed in the optical paths B2 and D2 respectively resulting in the odd multiples of 2 being converted into even multiples of 2 to allow a further sorting stage to be implemented. When considering the photons travelling along optical path B2, after passing through the hologram 38b, they then pass into unit 18d where a phase shift of $\alpha = \pi/4$ is introduced due to the rotation of the dove prisms in device 18d. Yet again, the photons are sorted into a further stage of odd and even classes of values of l in this case odd and even multiples of 4, with even multiples of 4 being output along C3, and odd multiples of 4 being output along optical path D3. As can be seen, each of the other output optical paths from devices 18a, b and c are treated similarly by passing through at least one further

device and therefore, by the end of the transmission through the apparatus, an 8 channel output is obtainable.

By adding further cascading stages to the apparatus, this procedure can be extended to allow an arbitrarily large number of orbital angular momentum states to be distinguished.

In Figure 7 experimental results achieved using a apparatus having two cascaded stages of devices 18 are illustrated. These photographic results were achieved with the light source input into the arrangement being a helium-neon laser with a power of less than 1mW. An intercavity cross-wire introduced rectangular symmetry to the laser cavity and forced the laser to oscillate in high order Hermite-Gaussian($HG_{m,n}$) modes. Such modes are characterized by the indices m and n which correspond to zeros of intensity in the electric field in the x and y directions, respectively. The Hermite-Gaussian($HG_{m,n}$) modes were then converted into Laguerre-Gaussian by passing them through a π/2 mode convertor based on cylindrical lenses. The resulting Laguerre-Gaussian modes had an $\exp(il\phi)$ phase structure and corresponding OAM of $l\hbar$ per photon. This conversion of Hermite-Gaussian beams give Laguerre-Gaussian($LG_{m,n}$) beams characterized by $l - |m-m|$ and $p = \min(m,n)$. Adjustments

to the intracavity cross wire allowed generation of $HG_{m,0}$ with m = 0,1,2,..., which in turn gives rise to LG^{l}_{0} beams with l = 0,1,2,...,. Each arm length of the unit 18 is approximately 30cm and comprises standard optical components as detailed previously. The $\Delta l = 1$ hologram 36 was manufactured using standard photographic techniques, and such a hologram 36 increases the l value of any $\exp(il\phi)$ mode by 1. The four output paths A2a, B2a, A2b, B2b of the system were directed onto a screen so that a camera could take an image of the output and the images generated are shown as images 7A, 7B, 7C, 7D and 7E respectively. As can be seen, the modes from l = 0 to l = 4 have been sorted into different output paths with the l = 4 image appearing the same port as the l = 0 beam as would be expected due to the 2 stage nature of the device.

In Figure 8, there is shown photographic results which were achieved by operating a one stage system at a single photon level. Achieving a single photon operating level, required using light having an intensity so low that on average less than one photon is present in each unit at any one time. This light intensity level was, in this case, achieved by inserting neutral-density filters to attenuate the power of the laser beam being input into

the device to less than 0.3nW. The experiment which generated the results of Figure 8 was carried out using a one stage device with the output ports of the device being directed into a camera that averaged over a number of frames. As can be seen, this device sorted between odd and even *l* with an efficiency limited only by the quality of optical components.

The orbital angular momentum sorting device as detailed above, could be considered to be the analogue of a polarizing beam splitter in that it selects an optical path on the basis of the orbital angular momentum with one path for each of the distinguishable states. It is in this way that the orbital angular momentum sorter can be used to create entanglement between the optical path and orbital angular momentum, in the same way that a polarising beam splitter can create entanglement between the optical path and polarisation. Such orbital angular momentum sorting apparatus can therefore generate highly entangled states and extend the optical realisation of quantum logic elements to orbital angular momentum quNits.

Furthermore, it can be seen that single photons in an orbital angular momentum eigenstate can be measured in any one of a number of different orthogonal states

corresponding to different values of l, with the orbital angular momentum in units of $\hbar$. The only limit to efficiency of the device or apparatus is the efficiency of the components. The ability to measure a single photon to be in any one of an arbitrarily large number of orthogonal states provides a useful tool in quantum information processing. The efficient measurement of the orbital angular momentum of a single photon allows access to a larger state space than that associated with optical polarisation. This means a greater density of information transfer, along with generation and analysis of entanglement, involving large numbers of states, is able to be utilized. Therefore, entanglement based applications, such as superdense coding, teleportation, and quantum computation, can all be improved due to the efficient measurement of the orbital angular momentum of a single photon.

In particular an optical communication system, such as that shown in Figure 9, can be constructed involving the optical device, or optical apparatus as described above. Such a communication system would be arranged to 'sort' between a predetermined number of states. Information encoded using the predetermined number of states would be transmitted by the optical transmission

means 37 to be received by an optical detection means 38, comprising an optical device or optical apparatus as detailed above. The information would then be decoded providing the original data.

In a further embodiment of the device, illustrated schematically in Figure 10, a quarter wave plate 40 and a prism 42 are disposed at the output path of the device, a mirror 44 disposed at the A output path directing the A output through the 1/4 wave plate and prism too.

By passing the outputs of the output paths A′ and B′ of the unit through a quarter wave plate and a prism, the resulting path of the photon also becomes dependent upon the spin angular momentum (SAM) state. This device results in four outputs ports A, B, C and D, each of which corresponds to a possible combination of spin +1/spin -1 (i.e. left hand/right hand polarisation) states and orbital even/odd states. In this arrangement there is also shown a preparation stage to the device which comprises a computer hologram 46, polariser 47, quarter wave plate QP1, and an electronically controlled half-wave plate 48. The polariser measures the light input by the laser i.e. pure linear polarised light. The quarter wave plate QP1 determines the polarisation state of the optical beam entering the device, in this case

circularly polarised light is transmitted. The half wave plate HP1 48 allows switching between +1 and -1 polarisation state for the input of light. This preparation stage allows the rapid selection between both the orbital angular momentum and polarisation states of the photons before they enter the sorting device. The 'sorting' device comprises standard optical components namely a first beam splitter 20, a first mirror 24, a second mirror 26, a first dove prism 28, a second dove prism 30, a second beam splitter 22 all of which are standard optical components. In this case the length of each arm of the interferometer arrangement of the device being approximately 100mm long. The light source used was a helium-neon laser with an output at 633 nano-metres and a power of less than 1mW. Neutral density filters were used to attenuate the power in the beams so that it corresponds to an average of one photon or less in the interferometer at any time. The output ports of the device are then directed into a camera that averages over 24 frames (per second) so that an intensity pattern can be recorded.

In Figure 11 the output from the orbital angular momentum and linear polarisation sorting process as performed by the device arrangement of Figure 9 can be

seen. As can be seen, the even and odd orbital angular momentum states have been sorted and simultaneously the horizontal and vertical linear polarisation states have been sorted into different output paths. The contrast of each channel was measured as a ratio of 10:1 and absolute efficiency of the device was 50%.

This technique can be extended further giving an arbitrarily large number of orbital angular momentum state results. This can be achieved, as detailed before, by cascading additional devices each having been provided with different rotation angles by virtue of the prisms included in the devices.

It should be understood that in each of the arrangements shown above higher contrast in output readings may be achieved by more rigidly designing the interferometer, and a higher absolute efficiency can be achieved with better quality and specifically designed optical components.

The device is further improved by utilising a prism as shown in Figure 12, in place of the known Dove prism arrangement, in the arms of the interferometer of the device.

As can be seen this prism 50 is provided with perpendicular edges 52, 54 thus allowing the prism to be

combined with beam splitters in a manner which allows the interferometer based units 18 to be built in the form of a monolithic block. Such a monolithic device 58 is shown in Figure 13. Furthermore, the prism 50 is polarization insensitive as the incident beam input into the prism 50 is normal to the prism surface 52.

The device 58, shown in Figure 13 , which is formed using two prisms 50 may be used in each stage of the orbital angular momentum 'sorter' apparatus with the monolithic block device being a more stable form of interferometer based device. Translational and angular displacement of the block device allows for the interferometer of the device to become aligned without the use of mirrors.

With reference to Figure 14, there is shown a fifth embodiment of the optical device which allows the total angular momentum of optical beam to be determined by the device. This device 60 comprises first beam splitter 20, first mirror 24, second mirror 26, first Dove prism 28, second Dove prism 30, and second beam splitter 22. The device further includes a first half wave plate 62 and second half wave plate 64 which act to rotate the polarisation / spin angular momentum state of the light mode. The phase shift between the two arms of the

interferometer thus becomes depended on the total angular momentum. This device therefore 'sorts' according to the total angular momentum.

Various modifications may be made to the arrangement as herein described, for example, in the absence of holograms, in a multi-device cascading arrangement, the device can be constructed to 'sort' beams where l takes on the values of 0 or 2^n where n is an integer.

Furthermore, an arrangement such as that shown in Figure 10 can be made omitting the quarter wave plates QP1 and QP2 and dealing only with a single polarisation i.e. linear polarisation. Another alternative in the arrangement of Figure 9 is that the camera may be replaced with avalanche photo-diodes in order to detect, and therefore sort individual photons.

In a further variation, each device may be provided with a multiple arm interferometer, which would allow each device to provide a 'sorting' ability according to the number of arms provided, for example, a three arm interferometer, would allow sorting into groups of a) 0, 3, 6,..., b) 1, 4, 7,.... and c) 2, 5, 8, ...

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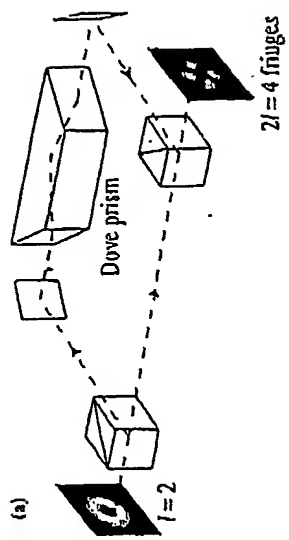

Figure 1
(prior art)

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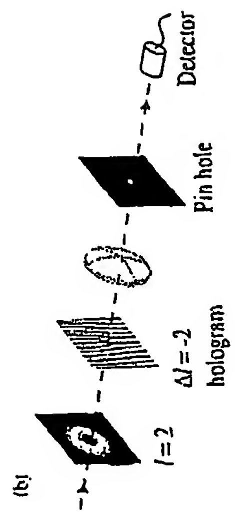
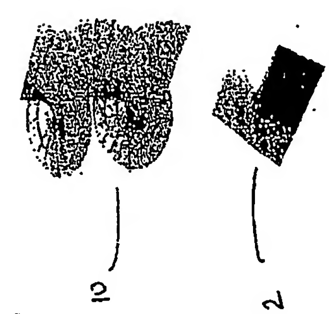
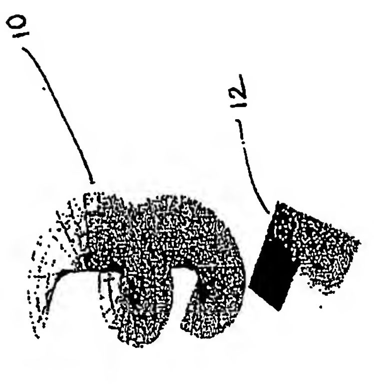


Figure 2.
(prior art)



$l = 1$ (unrotated)

FIGURE 3A



$l = 1$ (rotated thougb π)

FIGURE 3B

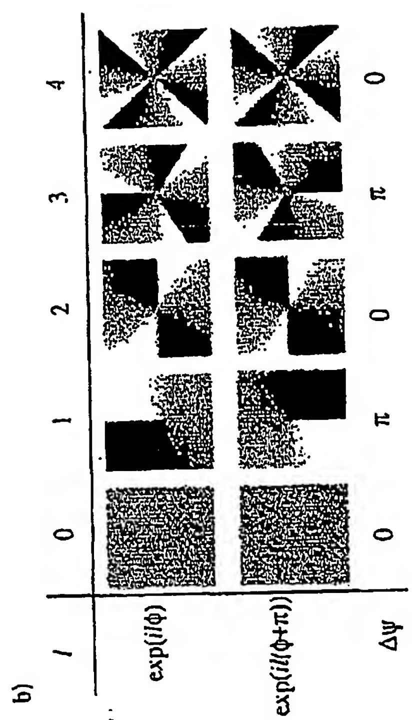


FIGURE 4

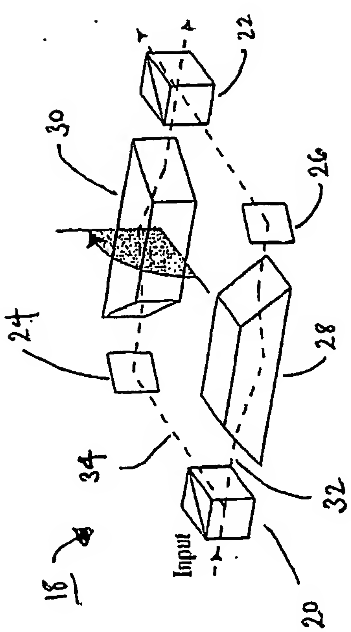


FIGURE 5

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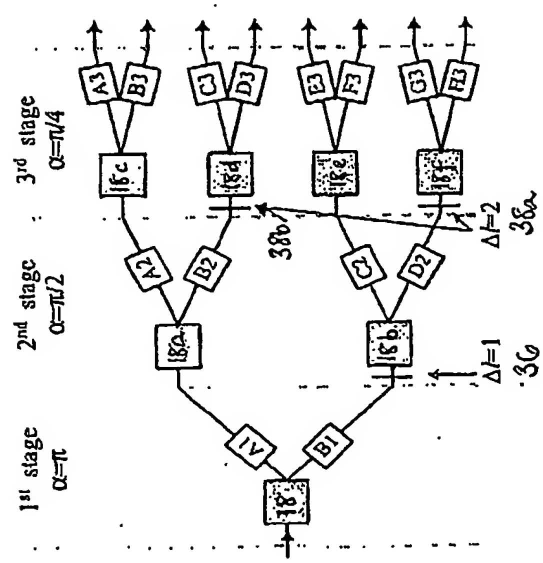


FIGURE 6

35

7A

7B

7C

7D

7E

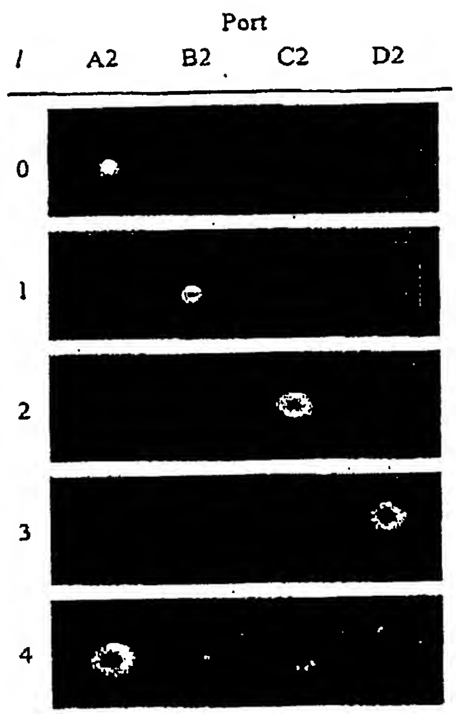


Figure 7.

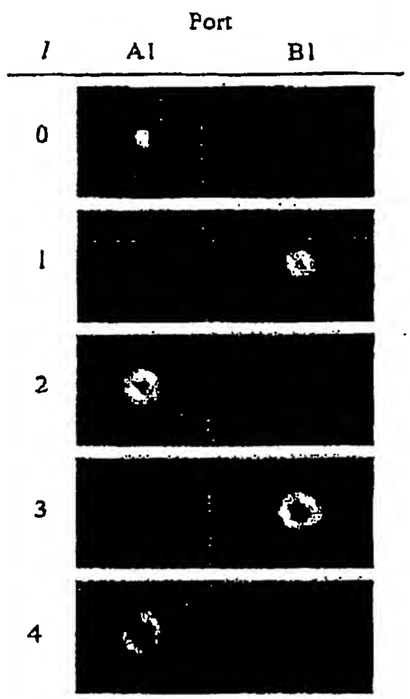


FIGURE 8

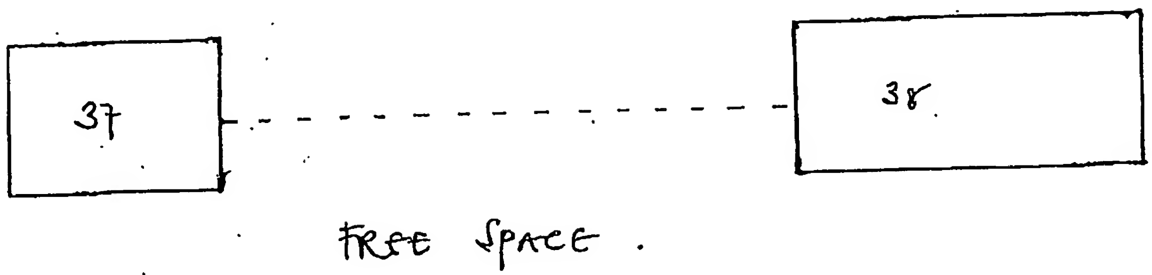


FIGURE 9.

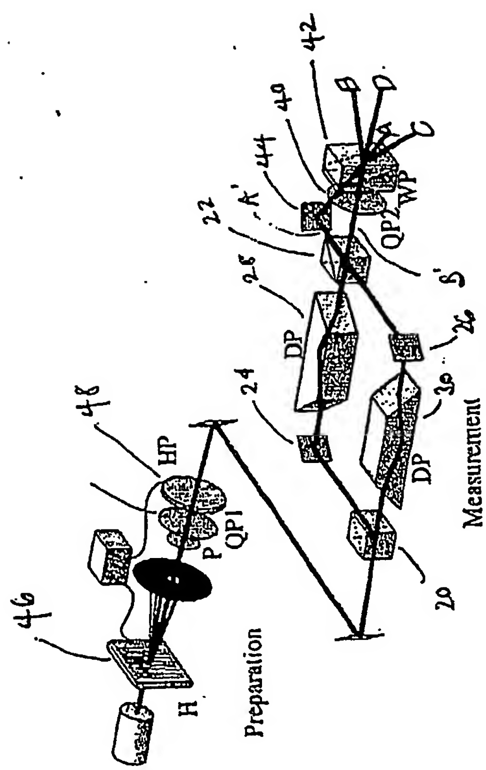

Preparation
H
46
P
QP1
HP
48
Measurement
20
24
DP
28
22
DP
30
26
44
40
42
QP2
WP

FIGURE 10

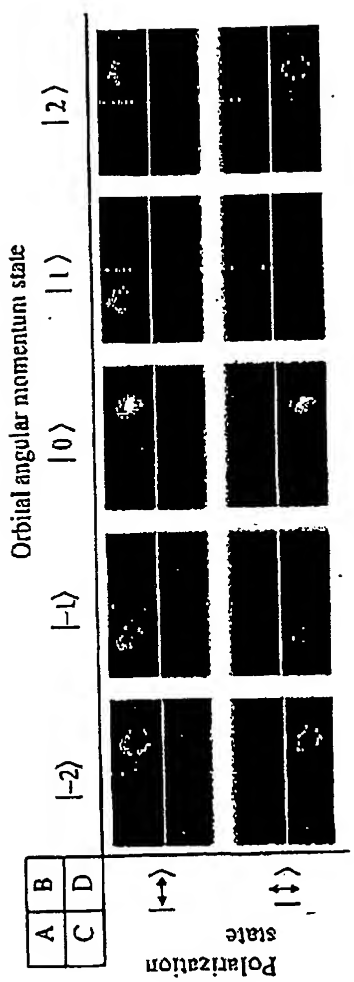

Orbital angular momentum state
|2⟩
|1⟩
|0⟩
|−1⟩
|−2⟩
A
B
C
D
Polarization state

FIGURE 11

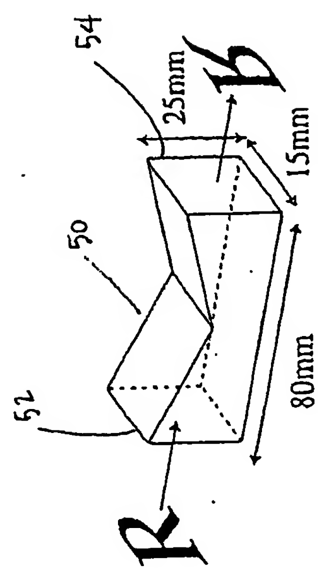
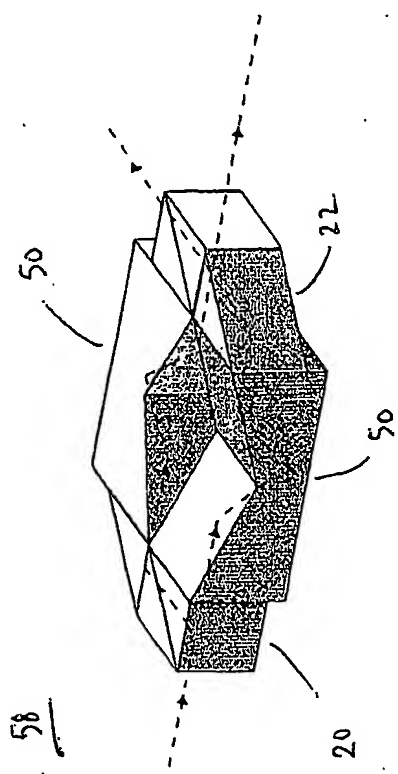


Figure 12


50
22
50
58
20

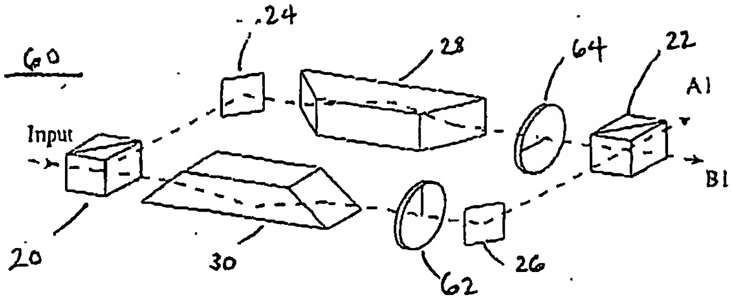


FIGURE 14